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TECHNICAL NOTE 3828

INVESTIGATION OF THE NiAl PHASE OF NICKEL-ALUMINUM ALLOYS

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SUMMARY

An investigation was made to determine the effects of composition and homogenization heat treatments on the hardness and tensile properties of cast alloys of the NiAl intermetallic phase. This phase exists over a wide range of composition (approximately 24 to 37 weight percent aluminum at 500° C) with stoichiometric NiAl at 31.5 percent aluminum.

Relatively small changes in composition within the NiAl phase resulted in appreciable hardness and strength changes. Room-temperature hardness of alloys containing 25 to 35 percent aluminum exhibited a sharp minimum at the stoichiometric composition. The average room-temperature tensile strength of as-cast alloys decreased with increasing aluminum content from 22,300 psi for the 25-percent-aluminum alloy to 14,250 psi for the 31.5-percent-aluminum alloy (stoichiometric NiAl). Homogenization of the cast alloys produced no large changes in the room-temperature tensile strength. The average room-temperature strength of the homogenized alloys varied from 29,450 psi for the 25-percent-aluminum alloy to 14,900 psi for the 31.5-percent-aluminum alloy. None of the as-cast or homogenized alloys showed any measurable tensile ductility at room temperature.

The average 1500° F tensile strength of homogenized alloys also decreased with increasing aluminum content, ranging from 29,050 psi for the 25-percent-aluminum alloy to 14,500 psi for the 31.5-percent-aluminum alloy. Alloys containing up to 31.5 percent aluminum exhibited considerable ductility in the 1500° F tensile tests.

Additions of 0.5 to 2.0 percent molybdenum to stoichiometric NiAl reduced the as-cast grain size and significantly increased both room- and elevated-temperature strength and ductility. The tensile strength at 1500° F was increased from 14,500 to 25,500 psi by the addition of 0.5 percent molybdenum.

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INTRODUCTION

The high-melting intermetallics have frequently been considered for high-temperature applications (refs. 1 and 2). In order to provide a better understanding of the characteristics of this class of materials, an investigation of the nickel-aluminum intermetallics (NiAl and Ni_3Al and their mixtures) was undertaken. The nickel-aluminum system was of special interest, for good modulus of rupture strength up to 1800° F and excellent oxidation resistance at temperatures up to 2000° F for an NiAl composition prepared by powder metallurgy have been reported (ref. 3). 3938

The present report is a continuation of previous work on the nickel-aluminum intermetallics NiAl and Ni_3Al reported in references 4 and 5. Reference 4 describes a process for casting nickel-aluminum alloys up to 30 percent aluminum, and presents data on the properties of the as-cast materials. Reference 5 reports the effects of homogenization heat treatments on the room- and elevated-temperature strength of two compositions in the Ni_3Al range.

This report discusses the properties of the NiAl phase. This phase is of particular interest, since it contains the highest melting alloy (stoichiometric NiAl: 31.5 percent aluminum, melting point of 2984° F) and because it exists over a broad range of compositions (fig. 1). Because of this latter feature, it was possible to study the variation of properties of the intermetallic phase as its composition was varied from 25 to 33 percent aluminum (both sides of stoichiometric NiAl). Tensile properties at room temperature were determined for as-cast alloys and at room temperature and 1500° F for homogenized alloys.

MATERIALS, APPARATUS, AND PROCEDURE

Specimen Preparation

Materials. - Electrolytic nickel (99.95 percent Ni by weight) chips and 1-inch cubes of high-purity aluminum (99.85 percent Al by weight) were used in the preparation of the experimental compositions.

Alloy compositions. - The desired compositions together with typical analyses are shown in table I.

During the course of the investigation small quantities of commercially pure molybdenum sheet were added to the 31.5-percent-aluminum alloy to refine the as-cast grain structure. A series of castings was made containing molybdenum in quantities of 0.5, 1.0, and 2.0 percent.

<u>Casting</u>. - A description of the casting techniques employed is reported in reference 5. The pouring temperature of stoichiometric NiAl was determined using a calibrated iridium - 40-percent-iridium-60-percent-rhodium immersion thermocouple in a zirconia protection tube. Thermocouple voltage was recorded with a recording potentiometer having a 1/2-second full-scale response. The temperature of the melt 2 minutes after the start of the exothermic reaction between nickel and aluminum (immediately prior to the beginning of pouring) is reported as the pouring temperature.

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<u>Heat treating</u>. - A conventional Globar furnace was used for homogenization heat treatments and for heating prior to mechanical working. Heat treatments above 2200° F were done in an argon atmosphere; heat treatments at lower temperatures were done in air. All specimens were furnace cooled following heat treatment.

<u>Machining</u>. - Cylindrical surfaces were ground using silicon carbide wheels. However, the use of silicon carbide wheels in grinding flat surfaces for hardness determinations resulted in badly checked surfaces and severe edge cracking. Flat surfaces free of cracks and grinding checks were produced by use of the following:

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(1) Abrasive: aluminum oxide, 80-mesh, vitreous-bonded, medium grinding wheel

(2) Coolant: water with soluble oil

(3) Speed: slow table speed and a grinding wheel speed of 6000 surface feet per minute

<u>Inspection</u>. - All test specimens were inspected by radiography and with a post emulsified fluorescent penetrant technique. Specimens with defects in the test area were discarded.

Specimen Evaluation

<u>Short-time tensile evaluation</u>. - Conical-end tensile specimens having a 1/4-inch-diameter gage section and a $1\frac{1}{4}$-inch gage length (fig. 2) were used. Room-temperature stress-strain curves were obtained using a conventional tensile machine and a recording extensometer. For high-temperature evaluations, the specimens and holders were enclosed in a platinum-wound tube furnace and the elongation was measured after fracture.

Notch tensile tests at 1500° F were also run on specimens of the homogenized 31.5-percent-aluminum alloy. The notched specimen is shown in figure 3. Originally it was intended that the bar contain a single sharp notch; however, a notch of 3/8-inch radius was inadvertently ground into the center of the gage length. It was believed that this notch was too gentle to yield the desired information. Consequently, in order to utilize these bars, a second notch having an included angle of 60° and a bottom radius of 0.010 inch was also ground into the same test bars. The cross-sectional area at the base of each notch was 50 percent of that of the smooth test section. The sharp notch was positioned halfway between the center and the end of the gage length.

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All tensile tests were run in air at a loading rate of 4000 psi per minute.

Stress-rupture evaluation. - The tensile specimens were also used for stress-rupture evaluation. These were run at 1500° F in air, using the procedure described in reference 6. Prior to machining specimens, the 31.5-percent-aluminum alloy was homogenized at 2200° F for 48 hours, whereas the alloy of 31.5 percent aluminum plus 0.5 percent molybdenum was homogenized at 2300° F for 24 hours.

X-ray examination. - A Geiger-counter X-ray diffractometer with an angular scanning range of 150° was used to obtain diffraction patterns from solid specimens of several of the alloys. Nickel-filtered copper radiation was used. Patterns were taken for both as-cast and homogenized specimens of the 30- and 31.5-percent-aluminum alloys in order to determine whether homogenization resulted in any change in lattice parameter.

Density evaluation. - Densities were determined by weighing the specimens in air and in water.

RESULTS AND DISCUSSION

Effects of Casting Method

In earlier work on nickel-aluminum alloys (ref. 4), sound castings containing 31.5 and 34 percent aluminum could not be made. The changes in the casting technique reported in reference 5 permitted successful castings of 31.5- and 33-percent-aluminum compositions. A longer holding time and a larger hot top were used and are believed to be primarily responsible for this improvement. The longer holding time (2 min. instead of 1) permitted the exothermic reaction between molten aluminum and nickel to become complete and the turbulence to subside before pouring. Holding times of 3 and 5 minutes did not further improve castability and increased contamination of the molten metal by reaction with

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the crucible. Although changes in the casting technique permitted the casting of NiAl compositions up to 33 percent aluminum, sound ingots of the 35-percent-aluminum alloy suitable for fabricating tensile bars could not be cast. All attempts to cast this alloy resulted in ingots containing conchoidal fractures. Although tensile bars could not be made, hardness specimens were ground from the fractured ingots.

Two determinations of the pouring temperature of stoichiometric NiAl were made. The results are listed in the following table:

Temperature of melt just before reaction, °F	Temperature of melt 15 seconds after start of reaction, °F	Highest temperature reached, °F	Pouring temperature (2 min after start of reaction), °F
2410	3180	3180	3070
2125	3185	3230	3040

The rapid increase in temperature of the melt accompanying the reaction between molten aluminum and nickel indicates the violent exothermic nature of the reaction. However, the use of a method in which solid nickel reacts with molten aluminum should tend to keep the maximum temperature considerably lower than a method sometimes employed in which aluminum is added to molten nickel.

The pouring temperatures were 86° and 56° F above the melting point of stoichiometric NiAl (2984° F). This comparatively small amount of superheating is helpful in obtaining a fine grain size. Metallographic examination of as-cast binary alloys containing from 25 to 35 percent aluminum showed only a single phase.

Comparison of the densities of as-cast alloys made for this study with those reported in reference 4 indicates that the changes in casting technique resulted in small increases in density (table II). However, the improved casting technique did not result in any significant changes in the room-temperature tensile strength or hardness of the as-cast alloys (table II).

Both room-temperature hardness and tensile strength of NiAl alloys decrease with increasing aluminum content up to the stoichiometric value (figs. 4 and 5). With aluminum additions in excess of the stoichiometric composition, the hardness shows a rapid increase. This variation of hardness with aluminum content has been reported by another author (ref. 7). The rapid increase in hardness accompanying the addition of aluminum in excess of the stoichiometric composition is attributed to the formation of a defect structure in these alloys, as described in reference 8. Stoichiometric NiAl exhibits an ordered, body-centered cubic lattice with nickel atoms at the cube corners and aluminum at the body center. Aluminum additions in excess of the stoichiometric composition do not replace nickel atom for atom, but leave some of the former nickel sites vacant. The presence of these vacant lattice sites causes lattice distortion with a resultant increase in hardness. Unfortunately, it was not possible to determine the room-temperature tensile properties of alloys containing more than 31.5 percent aluminum, for all test specimens 3938 broke in the conical ends. However, the extreme brittleness which resulted in these failures may be characteristic of NiAl alloys containing this defect structure.

Mechanical Properties of the Homogenized NiAl Phase

Effect of homogenization. - In order to eliminate the effects of coring commonly found in cast alloys, all NiAl alloys were given homogenization heat treatments designed to produce a uniform structure of minimum grain size. These were based on a preliminary study in which grain-coarsening temperatures were determined. Results of this study are reported in table III. Tensile and hardness specimens were then heat-treated 100° F below the lowest temperature for which grain growth was observed. The homogenization heat treatments are listed in table II. Microstructures of the homogenized alloys (fig. 6) showed equiaxed grains in both longitudinal and transverse cross sections of the specimens. X-ray diffraction examination of as-cast and homogenized specimens of the 30- and 31.5-percent-aluminum alloys revealed no measurable change in lattice parameter resulting from homogenization (table II).

Homogenization had little effect on the hardness of NiAl alloys (fig. 4). Effects on the room-temperature tensile strength vary with the composition of the alloy (table II and fig. 5). The average strength of the 25-percent-aluminum alloy was increased from 22,300 to 29,450 psi by homogenization, while that of the 28-percent-aluminum alloy was decreased from 21,650 to 17,850 psi. The room-temperature tensile strength of the homogenized 30-percent-aluminum alloy showed a wide variation in two tests, 42,200 and 16,700 psi as compared to an average of 14,400 psi for the as-cast specimens. Chemical analyses and X-ray and metallographic examinations revealed no significant differences between the two homogenized 30-percent-aluminum specimens.

None of the as-cast or homogenized NiAl alloys exhibited any measurable ductility in room-temperature tensile tests. Because of the extreme brittleness of the NiAl phase at room temperature, the results of room-temperature tensile tests may be influenced by premature failure due to microflaws or to bending stresses caused by misalinement.

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Effect of composition on the room-temperature strength of homogenized NiAl. - Except for the anomalously high value of 42,200 psi for the 30-percent-aluminum alloy, the homogenized NiAl alloys showed a trend of decreasing room-temperature tensile strength with increasing aluminum content up to the stoichiometric value. The strength decreased from an average of 29,450 psi for the 25-percent-aluminum alloy to 17,850 psi for the 28-percent-aluminum alloy to 14,900 psi for the 31.5-percent-aluminum alloy. This relatively large change in strength for a small change in composition within a single phase field is similar to the behavior previously reported for the Ni_3Al intermetallic phase (ref. 5).

Effect of temperature on strength of homogenized NiAl alloys. - Comparison of the tensile properties at room temperature and 1500° F of homogenized NiAl alloys containing up to 31.5 percent aluminum shows that the average 1500° F strengths are not greatly different from the room-temperature strengths (tables II and IV). However, in contrast to the extremely brittle behavior of these alloys at room temperature, alloys containing aluminum up to and including the stoichiometric value showed considerable ductility in the 1500° F tensile test. It is believed that the results of the 1500° F strength tests are probably more reliable than those of room-temperature tests, for the observed ductility should minimize the effects of misalinement and should enable the material to flow more easily around any microflaws. The 33-percent-aluminum alloy failed with no measurable elongation, but examination of the test section indicated the presence of numerous surface flaws which may have influenced the results of this test.

In order to study the effect of test temperature in more detail, additional tensile tests at other temperatures were run for stoichiometric NiAl (31.5 percent aluminum). This alloy exhibited its highest tensile strength, 19,800 psi, at 1200° F (table V and fig. 7). This is the lowest temperature at which the alloy exhibited tensile ductility (2.7 percent elongation). Above 1200° F, the tensile strength decreased slowly to 9600 psi at 1800° F, while the ductility increased rapidly to 52 percent elongation at 1800° F.

Notch tensile tests of stoichiometric NiAl. - Although stoichiometric NiAl exhibited considerable elongation (22 percent) and reduction of area (40 percent) in a 1500° F tensile test, examination of the specimens revealed extensive cracking in the vicinity of the fracture and an unusually large amount of cracking over the entire gage length (fig. 8). In order to investigate the notch sensitivity of this alloy, notch tensile specimens were prepared from ingots homogenized at 2200° F for 48 hours. As explained previously, these specimens contained both a sharp notch (0.010" radius) and a very gentle notch (3/8" radius). The minimum diameter of the test bar at the base of the notch was the same for both types of notches. The results of tensile tests of these specimens are reported below:

Temperature, °F	Tensile strength, psi	Reduction of area, percent	Location of fracture
1500	15,600	3.2	3/8" Radius notch
1500	18,200	3.9	3/8" Radius notch
1500	17,600	7.1	3/8" Radius notch

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Comparison of these results with the unnotched strength shown in table IV shows that the material was slightly strengthened by the gentle notch. The fact that the failure occurred in the gentle notch is indicative of even greater strengthening in the case of the sharp notch and demonstrates the ability of this alloy to overcome stress concentrations at 1500° F.

Effect of heat treatment without grain-size variation. - The high strength observed for one of the two 30-percent-aluminum specimens homogenized for 6 hours at 2400° F could not be explained on the basis of chemical analysis or microstructure. However, it appeared desirable to determine whether the strength was sensitive to a heat treatment which produced no apparent microstructural changes.

This was done by heat-treating specimens at 2100° F for 48 hours and comparing their properties with those of specimens heat-treated at 2400° F for 6 hours. Metallographic examination showed that both groups had the same grain size, and both contained only a single phase (figs. 9(a) and (b)).

Results of tensile tests of this alloy at both room temperature and 1500° F are given in table VI. The results of room-temperature tests show considerable scatter. Neither of the specimens homogenized at 2100° F approached the 42,200 psi strength of one of the two specimens homogenized at 2400° F. At 1500° F, specimens homogenized at 2400° F showed definite superiority, with an average strength of 24,850 psi and 11.8 percent elongation as compared to 16,300 psi and 2.2 percent elongation for specimens homogenized at 2100° F. The manner in which the strength of this alloy is affected by heat treatment which produces no change in the microstructure is not understood. It may result from differences in the extent of homogenization or may be associated with the superlattice formation that occurs in NiAl phase alloys (ref. 7).

Effect of grain-coarsening treatment. - Preliminary tests indicated that an increase in grain size resulting from growth of the as-cast grains during homogenization had little effect on the hardness of NiAl alloys (table III). In order to determine the effect of grain coarsening on strength, specimens of the 25-percent-aluminum alloy were heat-treated above the grain-coarsening temperature. Homogenization at 2100° F for 48 hours produced no change in the as-cast grain size (fig. 9(c)); homogenization at 2400° F produced grain coarsening (fig. 9(d)). The coarse-grained material had much lower tensile strength at both room temperature and 1500° F than the 2100° F homogenized material (table VII). The 1500° F tensile strength decreased from an average of 29,050 psi with 25.9 percent elongation for the specimen homogenized at 2100° F to an average of 18,700 psi with 0.5 percent elongation for the coarse-grained specimens. Inasmuch as the cast grain size present in the specimens homogenized at 2100° F was not very fine (fig. 9(c)), the strength and ductility of the alloy might be further increased by refinement of the as-cast grain size.

Effect of molybdenum additions to stoichiometric NiAl. - Since it was believed that a fine grain size would result in superior strength and ductility, an attempt was made to refine the as-cast grain size of stoichiometric NiAl by the additions of small percentages of an alloying element. For a 17.5-percent-aluminum alloy small molybdenum additions had been found to be particularly effective (ref. 4). In the investigation reported herein, increasing the molybdenum content of the stoichiometric NiAl alloy from 0.5 to 1.0 to 2.0 percent resulted in a continuous decrease in the as-cast grain size (fig. 10). Simultaneously, a second phase appeared at the grain boundaries (fig. 11), the amount of which increased with increasing molybdenum content. An attempt to identify the second phase in the alloy containing 2.0 percent molybdenum by X-ray diffraction analyses was unsuccessful. Two weak lines not characteristic of NiAl were observed but could not be identified.

Molybdenum additions to stoichiometric NiAl resulted in significant increases in the strength and ductility of the alloy (table VIII and fig. 12). For example, the room-temperature tensile strength was increased from 14,900 to 34,400 psi by the addition of 2 percent molybdenum. The alloys containing molybdenum also exhibited a small amount of room-temperature ductility in contrast to the completely brittle behavior of unmodified NiAl.

The 1500° F tensile strength of all three molybdenum alloys was also superior to that of stoichiometric NiAl. The strength was about 25,000 psi for all the molybdenum alloys as compared with an average of 14,500 psi for the unmodified 31.5-percent-aluminum alloy. At 1700° F, the addition of 1.0 percent molybdenum increased the strength from 9800 psi with 27.2 percent elongation to 17,600 psi with 51.7 percent elongation. The high degree of plasticity exhibited by this molybdenum-modified alloy is shown in figure 8(b).

The beneficial effects of molybdenum additions to stoichiometric NiAl are probably a result of the combined effects of decreased grain size and the appearance of a second phase at the grain boundaries. Increased ductility may be due only to the finer grain size. However, the unidentified precipitate might be exercising a beneficial effect by tieing up embrittling impurities.

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The large increases in strength and ductility resulting from small additions of molybdenum demonstrate the possibility of greatly improving the mechanical properties of the NiAl intermetallic by alloying. The fact that the alloys containing molybdenum exhibited a small amount of room-temperature ductility is particularly significant, for it indicates the possibility of overcoming the serious room-temperature brittleness of these alloys.

Stress-rupture properties of stoichiometric NiAl. - The 100-hour rupture strength at 1500° F of stoichiometric NiAl was determined. A value of 4500 psi was obtained by interpolating the results shown in table IX. The low stress-rupture strength of the stoichiometric alloy at 1500° F indicates the need for alloying additions to make the NiAl intermetallic phase of interest for high-temperature applications. A single rupture test at 1500° F of the 31.5 percent aluminum plus 0.5 percent molybdenum alloy indicated a substantial increase in rupture strength over that of the unmodified alloy (table IX). It is of interest to note that the addition of 4 percent zirconium to a NiAl alloy prepared by powder metallurgy methods is reported to result in greatly improved strength up to 1832° F (ref. 9).

SUMMARY OF RESULTS

NiAl alloys containing from 25 to 33 percent aluminum were satisfactorily cast by an improved casting technique previously reported. The effects of composition and of homogenization heat treatments on the room-temperature hardness and room- and elevated-temperature tensile strength of these alloys were determined. The following results were obtained:

1. Relatively small changes in composition within the NiAl phase resulted in appreciable changes in the mechanical properties of these alloys. The hardness at room temperature decreased with increasing aluminum content up to the stoichiometric composition and then increased rapidly with further aluminum additions. Room-temperature tensile strength of both as-cast and homogenized alloys, and tensile strength at 1500° F of homogenized alloys also decreased with increasing aluminum content up to the stoichiometric composition. For example, the room-temperature tensile strength of homogenized alloys varied from 29,450

psi for the 25-percent-aluminum alloy to 14,900 psi for the 31.5-percent-aluminum alloy. At 1500° F the tensile strengths ranged from 29,050 psi for the 25-percent-aluminum alloy to 14,500 psi for the stoichiometric alloy. Good tensile data for alloys containing aluminum in excess of the stoichiometric value were not obtained. None of the alloys showed any room-temperature ductility. At 1500° F, alloys containing up to 31.5 percent aluminum exhibited considerable tensile ductility.

2. Homogenization of the as-cast alloys did not produce large changes in the room-temperature tensile strength. Small increases or decreases were observed, depending on the composition of the alloy.

3. Stoichiometric NiAl had its highest tensile strength, 19,800 psi, at 1200° F. This was the lowest temperature for which tensile ductility was observed for this alloy. Above 1200° F, the tensile strength fell off slowly to a value of 9600 psi at 1800° F. The 100-hour rupture strength of stoichiometric NiAl was 4500 psi at 1500° F.

4. The 1500° F tensile strength of the 30-percent-aluminum alloy was affected by heat treatment below the grain growth temperature. Although no microstructural differences were observed, specimens homogenized at 2400° F had an average 1500° F tensile strength of 24,850 psi compared to 16,300 psi for those homogenized at 2100° F.

5. For the 25-percent-aluminum alloy, heat treatment which produced grain coarsening decreased the tensile strength at both room temperature and 1500° F. The 1500° F strength decreased from 29,050 psi with 25.9 percent elongation for specimens homogenized at 2100° F to 18,700 psi with 0.5 percent elongation for specimens given a grain-coarsening heat treatment at 2400° F.

6. Additions of 0.5, 1.0, and 2.0 percent molybdenum to stoichiometric NiAl decreased the as-cast grain size and resulted in appreciable increases in both room- and elevated-temperature tensile strength and ductility.

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TABLE I. - CHEMICAL ANALYSIS OF SPECIMENS

Desired composition		Actual composition, weight percent		
Percent by atoms	Percent by weight	Ni	Al	Fe
57.96 Ni + 42.04 Al	75 Ni + 25 Al	74.58	25.15	0.02
54.16 Ni + 45.84 Al	72 Ni + 28 Al	71.70	28.40	0.02
51.74 Ni + 48.26 Al	70 Ni + 30 Al	70.02	30.45	0.08
50 Ni + 50 Al	68.5 Ni + 31.5 Al	68.45	31.20	0.09
48.27 Ni + 51.73 Al	67 Ni + 33 Al	67.06	33.65	0.02
46.05 Ni + 53.95 Al	65 Ni + 35 Al	64.88	36.05	0.01

TABLE II. - ROOM-TEMPERATURE PROPERTIES OF INTERMETALLIC PHASE NiAl

Composition Ni	Composition Al	Condition	Tensile strength, psi	Extensometer elongation, percent	Measured elongation, percent	Hardness, Rockwell A-	Density, g/ml	Lattice parameter, kX units
75	25	As-cast	22,700	0	0	72.0	6.40	-----
75	25	As-cast[a]	24,100	0	0	72.0	6.33	-----
75	25	As-cast[a]	20,200	0	0	72.0	----	-----
75	25	Homogenized at 2100° F for 48 hr	31,800	0	0	72.5	6.37	-----
75	25	Homogenized at 2100° F for 48 hr	27,100	0	0	72.5	----	-----
72	28	As-cast	22,600	0	0	69.7	6.16	-----
72	28	As-cast[a]	20,000	0	0	71.0	6.12	-----
72	28	As-cast[a]	22,400	0	0	71.0	----	-----
72	28	Homogenized at 2200° F for 48 hr	18,200	0	0	70.6	6.15	-----
72	28	Homogenized at 2200° F for 48 hr	17,500	0	0	70.6	----	-----
70	30	As-cast	14,400	0	0	66.1	5.99	2.880
70	30	As-cast[a]	16,300	0	0	----	5.98	-----
70	30	As-cast[a]	12,500	0	0	----	----	-----
70	30	Homogenized at 2400° F for 6 hr	42,200	0	0	66.3	6.03	2.880
70	30	Homogenized at 2400° F for 6 hr	16,700	0	0	66.3	----	-----
68.5	31.5	As-cast	15,200	0	0	61.0	----	2.881
68.5	31.5	As-cast	13,300	0	0	61.0	5.93	-----
68.5	31.5	As-cast[a]	Unsound ingot	-	-	----	5.89	-----
68.5	31.5	Homogenized at 2200° F for 48 hr	15,700	0	0	60.6	5.93	2.881
68.5	31.5	Homogenized at 2200° F for 48 hr	14,100	0	0	60.6	----	-----
67	33	As-cast	[b]3,000	0	0	71.0	5.72	-----
67	33	As-cast	[b]1.400	0	0	71.0	----	-----
67	33	Homogenized at 2100° F for 48 hr	[b]1,860	0	0	71.8	5.70	-----
65.	35	As-cast	Unsound ingot	-	-	77.0	----	-----

[a]Data taken from reference 4.

[b]Broke in grips.

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TABLE III. - EFFECT OF HOMOGENIZATION TEMPERATURE ON GRAIN SIZE AND HARDNESS OF CAST NiAl COMPOSITIONS

Composition, weight percent Al	Homogenization temperature, °F	Time, hr	Effect on grain size	Hardness, Rockwell A-
25	As-cast			72.0
25	2100	48	None	72.5
25	2200	48	Coarse grains	72.2
25	2400	6	Coarse grains	72.0
28	As-cast			69.7
28	2200	48	None	70.6
28	2300	24	Coarse grains	70.7
30	As-cast			66.1
30	2100	48	None	66.5
30	2400	6	None	66.3
30	2500	6	Coarse grains	66.0
31	As-cast			61.0
31.5	2200	48	None	60.6
31.5	2300	24	Some grain growth	60.4
31.5	2400	6	Coarse grains	61.2
33	As-cast			71.0
33	2100	48	None	71.8
33	2200	48	Some grain growth	70.8
33	2300	24	Coarse grains	72.1
35	As-cast			77.0
35	2000	48	None	77.4
35	2100	48	Some grain growth	77.2
35	2200	48	Coarse grains	76.9

TABLE IV. - 1500° F TENSILE PROPERTIES OF NiAl INTERMETALLIC PHASE

Composition		Condition: homogenized at -	Tensile strength, psi	Measured elongation, percent	Reduction in area, percent
Ni	Al				
75	25	2100° F for 48 hr	29,200	20	18.3
75	25	2100° F for 48 hr	28,900	[a]31.7	26.8
72	28	2200° F for 48 hr	24,300	[a]4.0	3.4
72	28	2200° F for 48 hr	23,900	[a]4.0	3.8
70	30	2400° F for 6 hr	25,200	11.9	7.6
70	30	2400° F for 6 hr	24,500	[a]11.9	10.6
68.5	31.5	2200° F for 48 hr	15,400	[a]20.4	39.4
68.5	31.5	2200° F for 48 hr	13,600	[a]24.5	(b)
67	33	2100° F for 48 hr	[c]7,000	0	0

[a]Some grain separation.
[b]Could not be measured.
[c]Specimen had surface flows in gage section.

TABLE V. - EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES

OF STOICHIOMETRIC NiAl (31.5 PERCENT ALUMINUM)

Condition: homogenized at -	Test temperature	Tensile strength, psi	Measured elongation, percent	Reduction in area, percent
2200° F for 48 hr	Room temperature	15,700	0	0
2200° F for 48 hr	Room temperature	14,100	0	0
2200° F for 48 hr	1000° F	14,700	0	0
2200° F for 48 hr	1200° F	19,800	2.7	2.4
2200° F for 48 hr	1300° F	19,100	[a]12.3	9.7
2200° F for 48 hr	1400° F	16,900	[a]11.1	15.8
2200° F for 48 hr	1500° F	15,400	[a]20.4	39.4
2200° F for 48 hr	1500° F	13,600	[a]24.5	(b)
2200° F for 48 hr	1700° F	9,800	[a]27.2	(b)
2200° F for 48 hr	1800° F	9,600	[a]52	(b)

[a]Some grain separation.
[b]Could not be measured.

TABLE VI. - EFFECT OF HOMOGENIZING TEMPERATURE ON ROOM TEMPERATURE AND 1500° F TENSILE PROPERTIES OF 30-PERCENT-ALUMINUM NiAl ALLOY

Condition	Test temperature	Tensile strength, psi	Extensometer elongation, percent	Measured elongation, percent	Reduction in area, percent
As-cast	Room temperature	14,400	0	0	0
Homogenized at 2100° F for 48 hr	Room temperature	17,300	0	0	0
Homogenized at 2100° F for 48 hr	Room temperature	11,600	0	0	0
Homogenized at 2400° F for 6 hr	Room temperature	16,700	0	0	0
Homogenized at 2400° F for 6 hr	Room temperature	42,200	0	0	0
Homogenized at 2100° F for 48 hr	1500° F	17,200	--	[a]2.7	2.4
Homogenized at 2100° F for 48 hr	1500° F	15,400	--	[a]1.8	2.0
Homogenized at 2400° F for 6 hr	1500° F	25,200	--	11.8	7.6
Homogenized at 2400° F for 6 hr	1500° F	24,500	--	[a]11.9	10.6

[a]Some grain separation.

TABLE VII. - EFFECT OF GRAIN-COARSENING HEAT TREATMENT ON ROOM-TEMPERATURE AND 1500° F TENSILE PROPERTIES OF 25-PERCENT-ALUMINUM NiAl ALLOY

Condition: homogenized at -	Grain size	Test temperature	Tensile strength, psi	Extensometer elongation, percent	Measured elongation, percent	Reduction in area, percent
2100° F for 48 hr	As-cast	Room temperature	31,800	0	0	0
2100° F for 48 hr	As-cast	Room temperature	27,100	0	0	0
2400° F for 6 hr	Coarse	Room temperature	17,300	0	0	0
2400° F for 6 hr	Coarse	Room temperature	9,000	0	0	0
2100° F for 48 hr	As-cast	1500° F	29,200	--	20	18.3
2100° F for 48 hr	As-cast	1500° F	28,900	--	[a]31.7	26.8
2400° F for 6 hr	Coarse	1500° F	21,100	--	1.0	2.0
2400° F for 6 hr	Coarse	1500° F	16,300	--	0	0

[a]Some grain separation.

TABLE VIII. - EFFECT OF MOLYBDENUM ADDITIONS ON ROOM-TEMPERATURE AND ELEVATED-TEMPERATURE TENSILE PROPERTIES OF STOICHIOMETRIC NiAl (31.5 PERCENT ALUMINUM)

Condition: homogenized at -	Molybdenum added, percent	Test temperature	Tensile strength, psi	Extensometer elongation, percent	Measured elongation, percent	Reduction in area, percent
2200° F for 48 hr	None	Room temperature	15,700	0	0	0
2200° F for 48 hr	None	Room temperature	14,100	0	0	0
2300° F for 24 hr	0.5	Room temperature	18,400	0.05	1.9	----
2300° F for 24 hr	1.0	Room temperature	21,200	0	0.3	<0.1
2300° F for 24 hr	2.0	Room temperature	34,400	0	0.5	<0.1
2200° F for 48 hr	None	1500° F	15,400	----	[a]20.4	39.4
2200° F for 48 hr	None	1500° F	13,600	----	[a]24.5	(b)
2300° F for 24 hr	0.5	1500° F	25,500	----	[a]27.8	57.5
2300° F for 24 hr	1.0	1500° F	23,700	----	[a]48.2	77.6
2300° F for 24 hr	2.0	1500° F	25,100	----	44.7	82
2200° F for 48 hr	None	1700° F	9,800	----	[a]27.2	(b)
2300° F for 24 hr	1.0	1700° F	17,600	----	51.7	93.2
2300° F for 24 hr	2.0	1700° F	17,400	----	[a]20.2	(b)

[a]Some grain separation.

[b]Could not be measured.

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TABLE IX. - RUPTURE LIVES OF STOICHIOMETRIC

NiAl (31.5 PERCENT Aluminum) AT 1500° F

Composition, weight percent			Stress, psi	Life, hr	Elongation, percent	Reduction in area, percent
Ni	Al	Mo				
68.5	31.5	0	7,500	4.6	[a]44.5	Could not be measured
68.5	31.5	0	6,000	13.2	46.2	Could not be measured
68.5	31.5	0	4,000	186.1	[a]Could not be measured	Could not be measured
68.5	31.5	0.5	12,500	23.1	15.2	31.9

[a]Some grain separation.

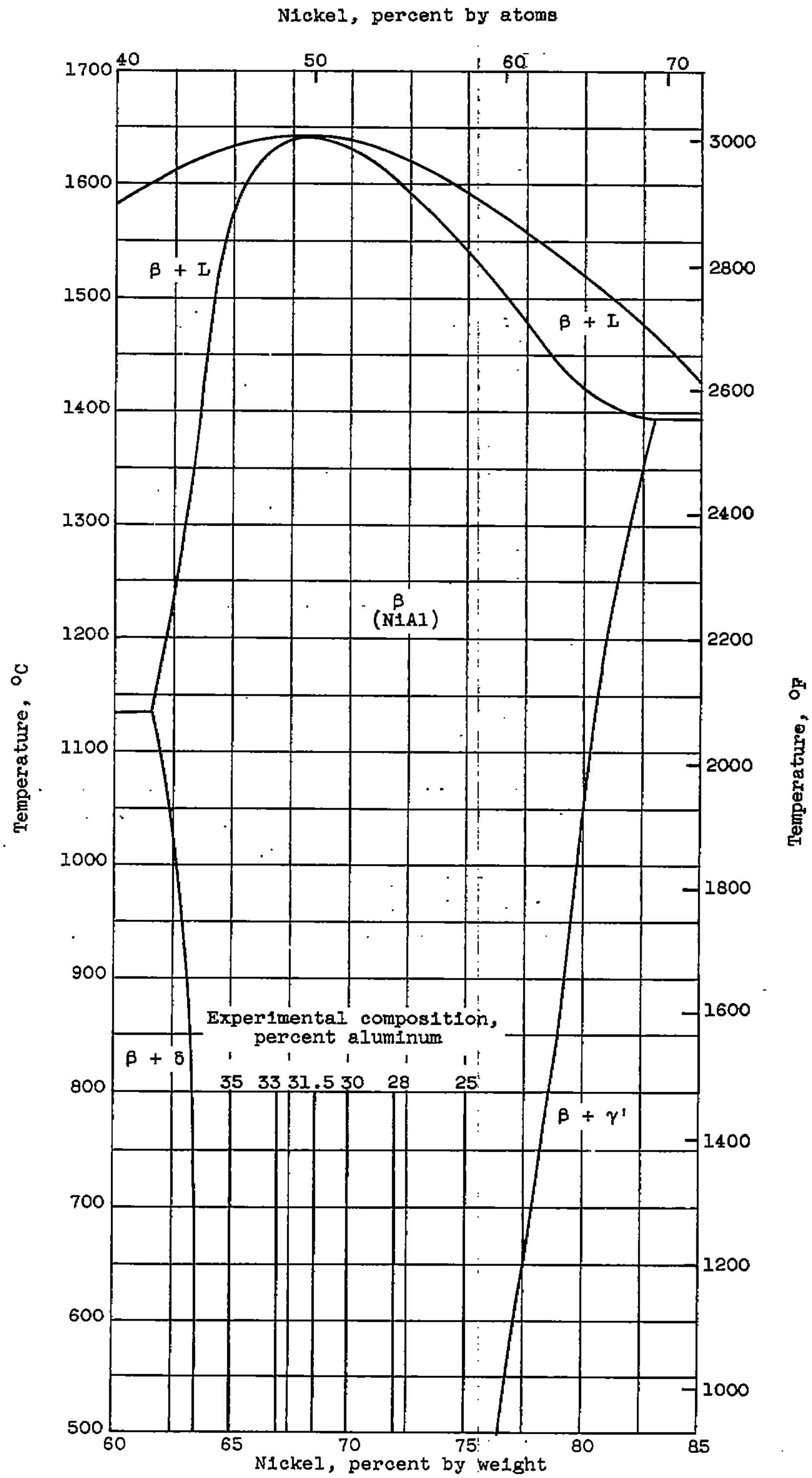

Figure 1. - Area of nickel-aluminum phase diagram under investigation (ref. 10).

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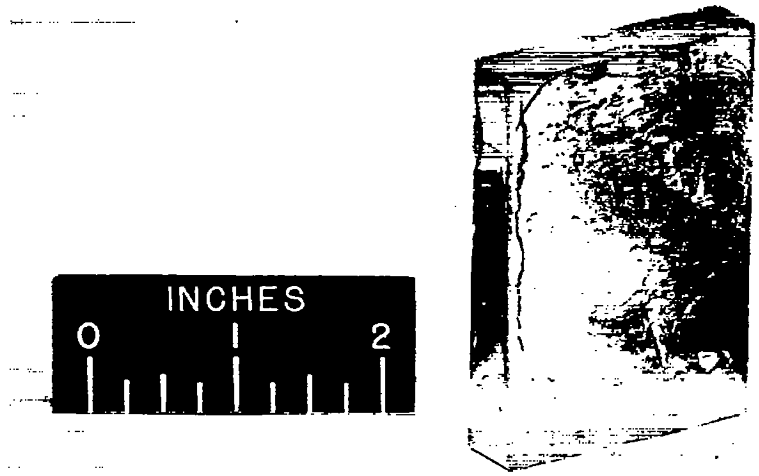

(a) Stoichiometric NiAl 1/2 by 2 inch ingot.

C-43233

(b) Ground tensile bar.

Figure 2. - Typical NiAl specimens.

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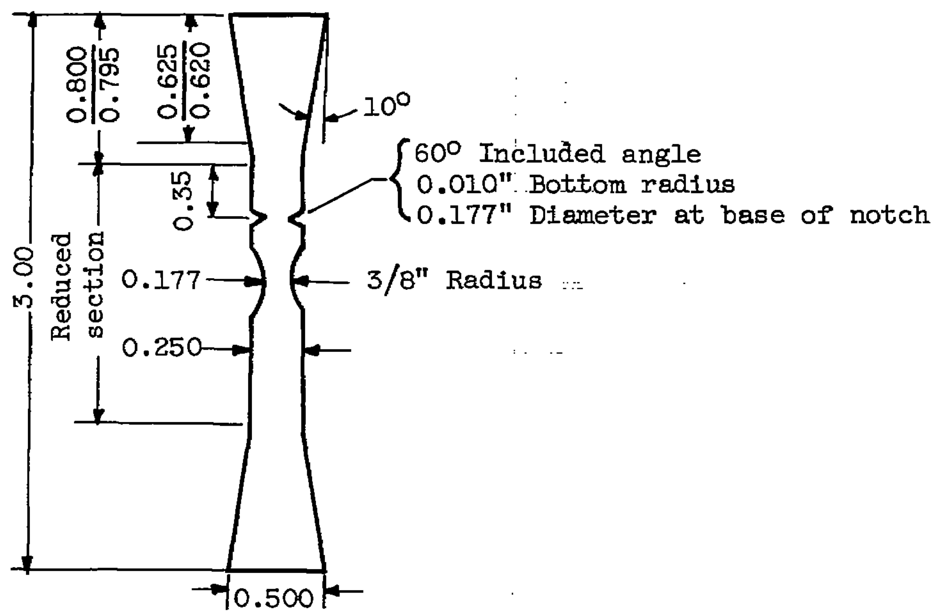

Figure 3. - Notched tensile specimen.
(Dimensions in inches.)

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CM-4

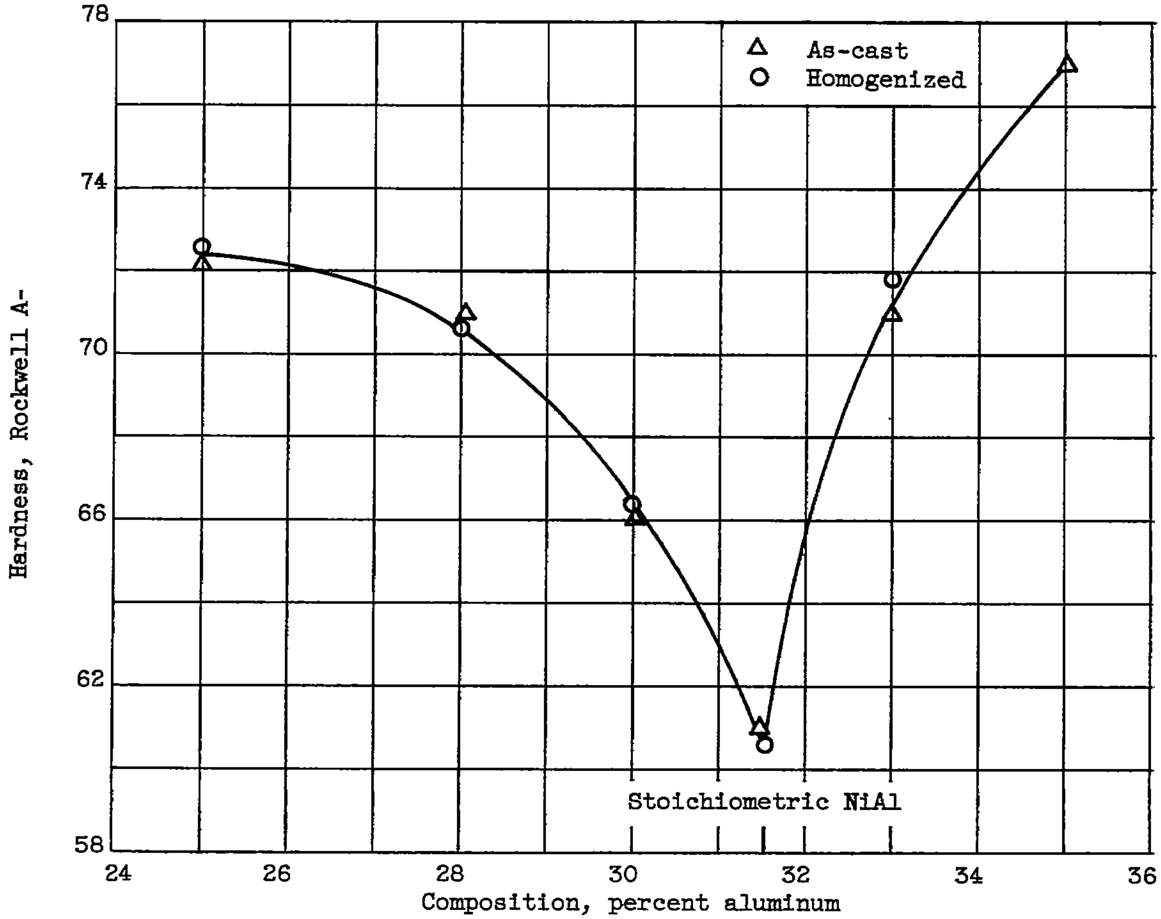

Figure 4. - Effect of composition on hardness of NiAl phase.

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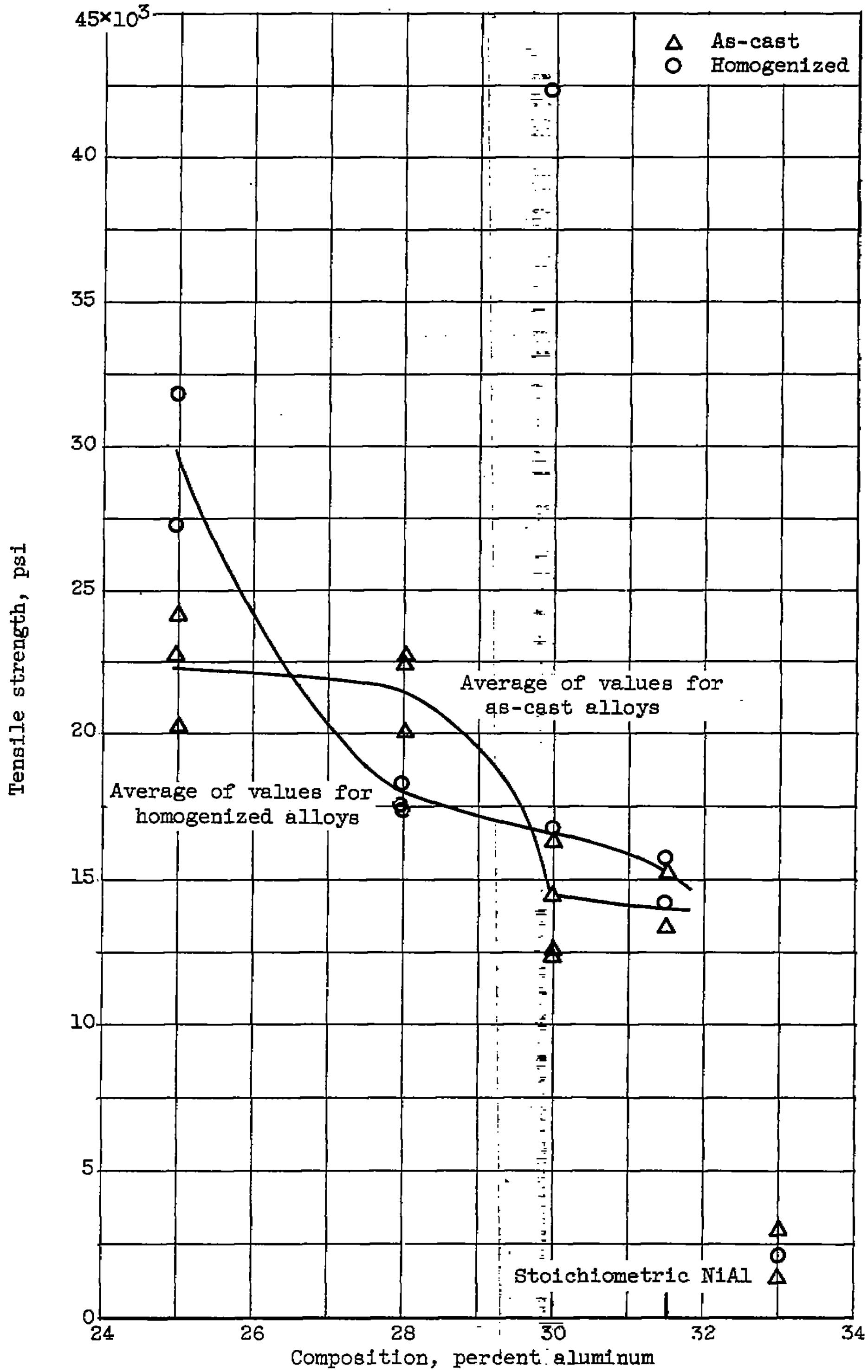

Figure 5. - Effect of composition on room-temperature strength of as-cast and homogenized alloys of NiAl phase.

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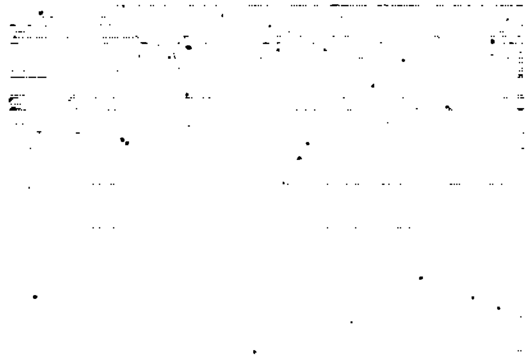
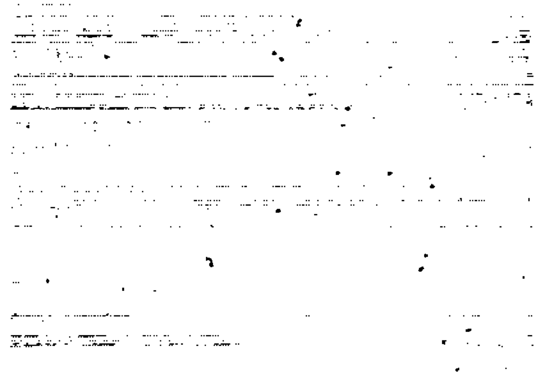
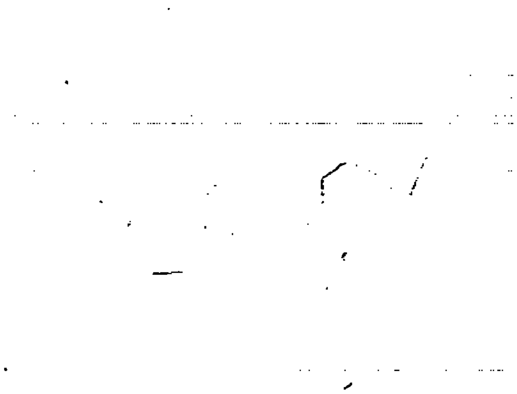
CM-4 back



(a) 25-Percent-aluminum NiAl, homogenized at 2100° F for 48 hours.

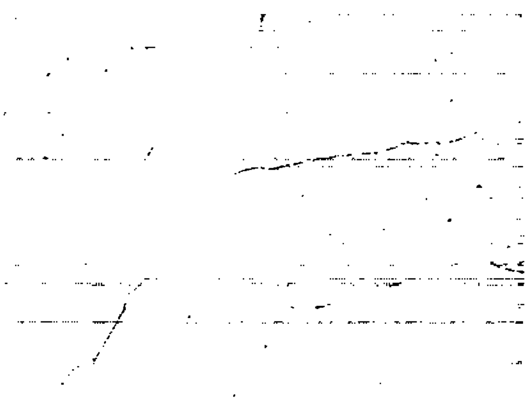


(b) 28-Percent-aluminum NiAl, homogenized at 2200° F for 48 hours.

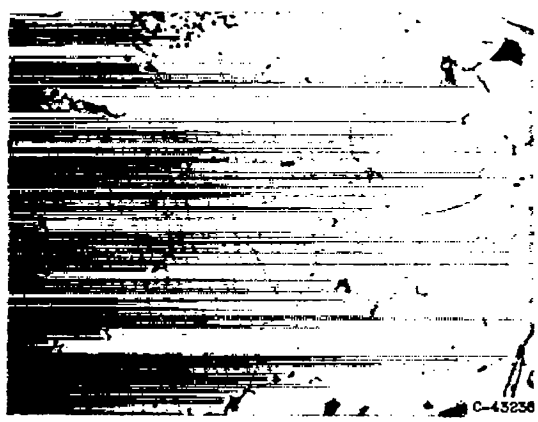


(c) 30-Percent-aluminum NiAl, homogenized at 2400° F for 6 hours.

(d) 31.5-Percent-aluminum NiAl, homogenized at 2200° F for 48 hours.



(e) 33-Percent-aluminum NiAl, homogenized at 2100° F for 48 hours.



(f) 35-Percent-aluminum NiAl, homogenized at 2000° F for 48 hours.

Figure 6. - Microstructure of homogenized NiAl phase compositions. Vilella's reagent; X100.

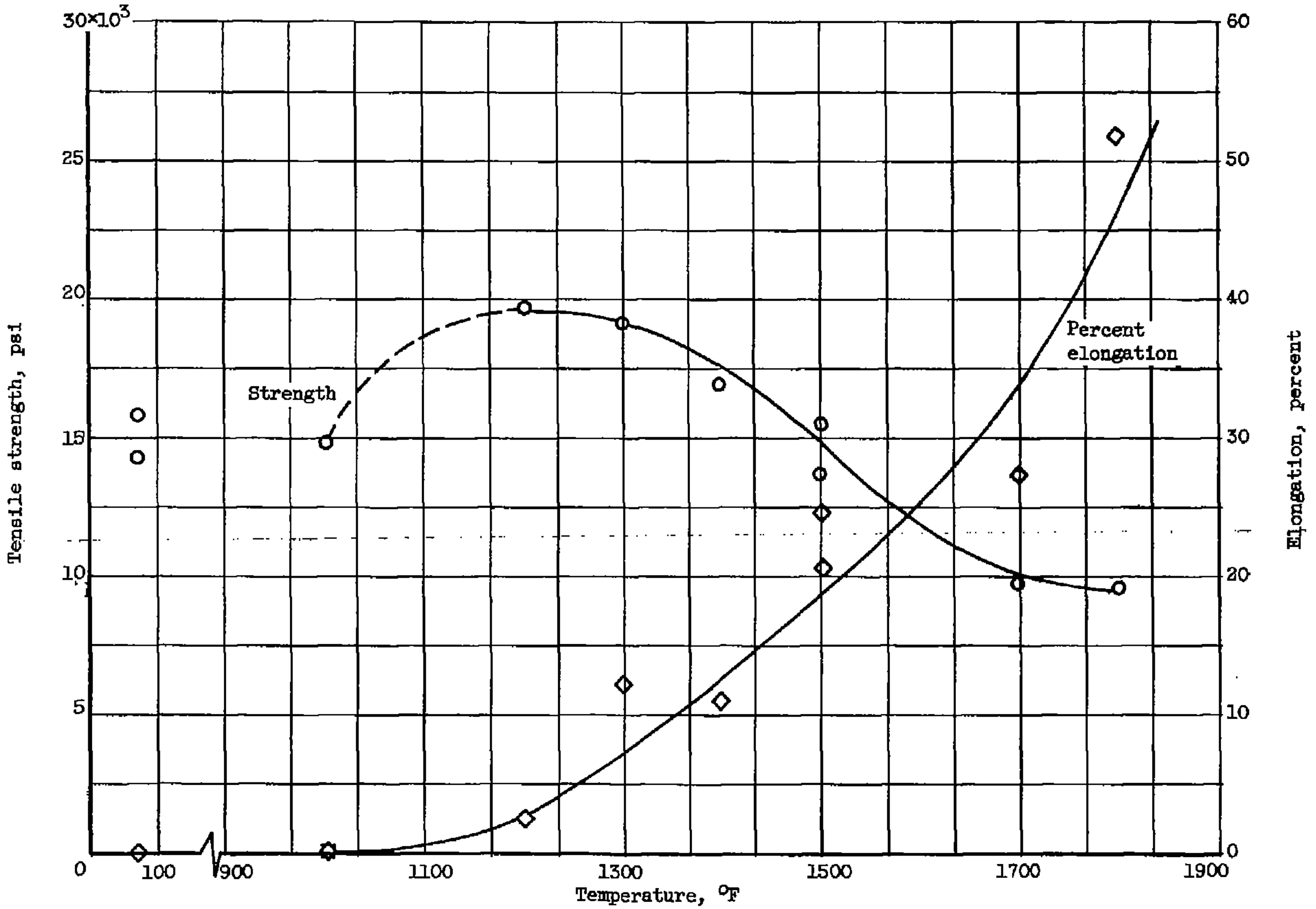


Figure 7. - Effect of temperature on tensile properties of stoichiometric (31.5-percent-aluminum) NiAl.

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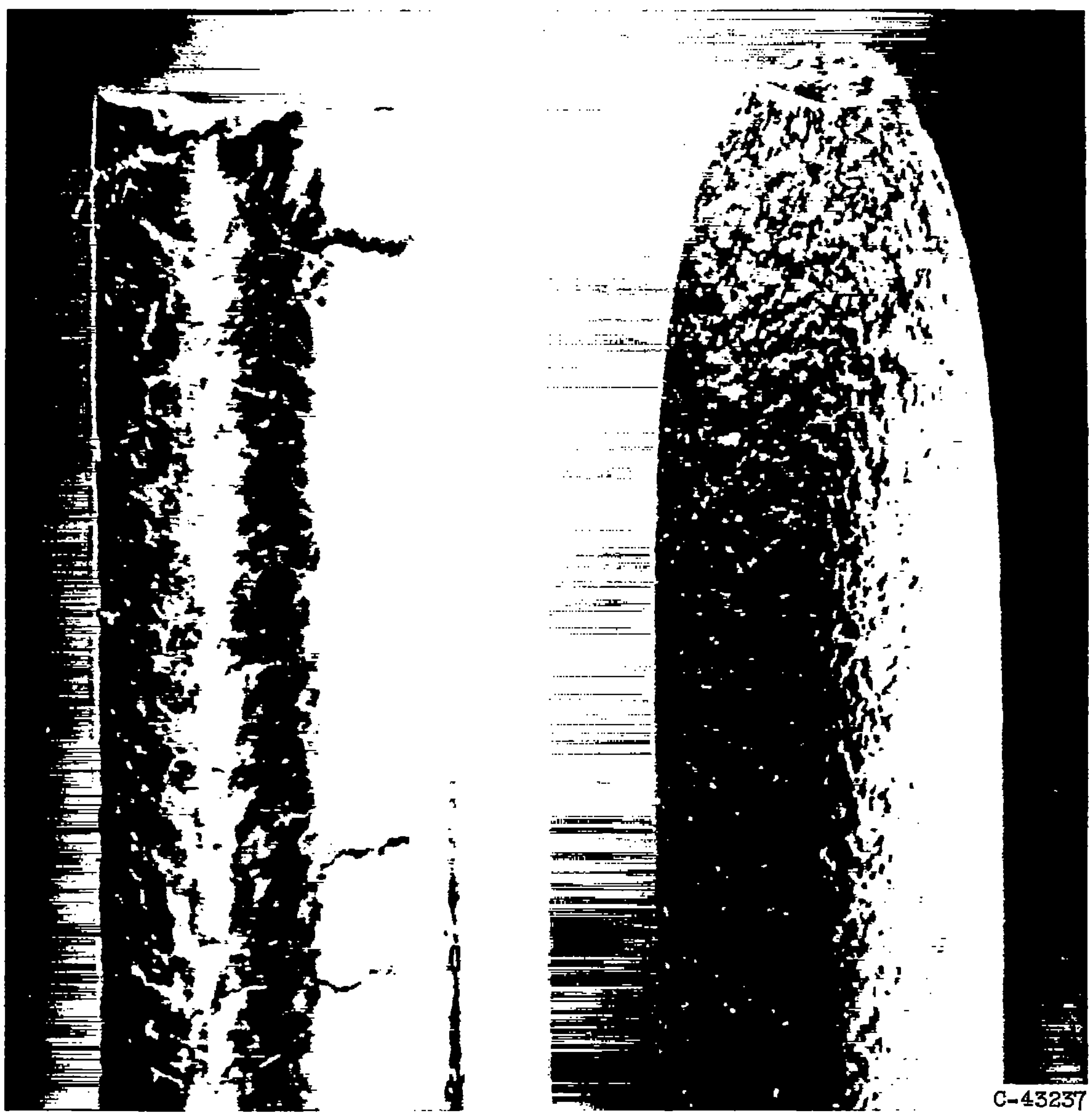
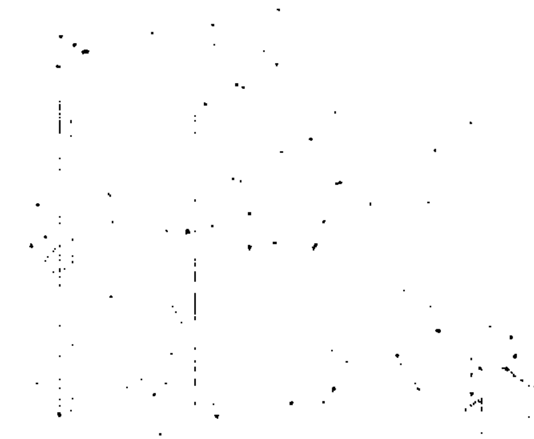


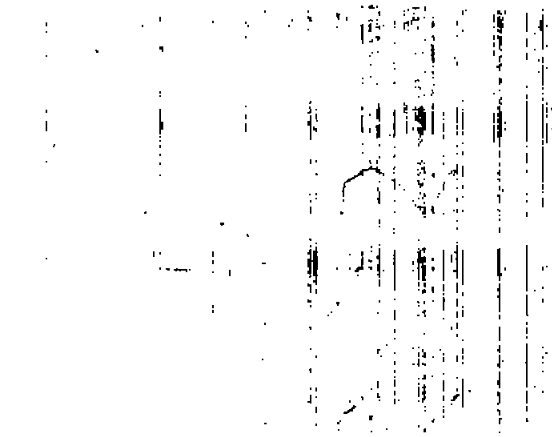
(a) 1500° F tensile test. 25-Percent-aluminum alloy.

(b) 1700° F tensile test. 31.5-Percent-aluminum and 1-percent-molybdenum alloy.

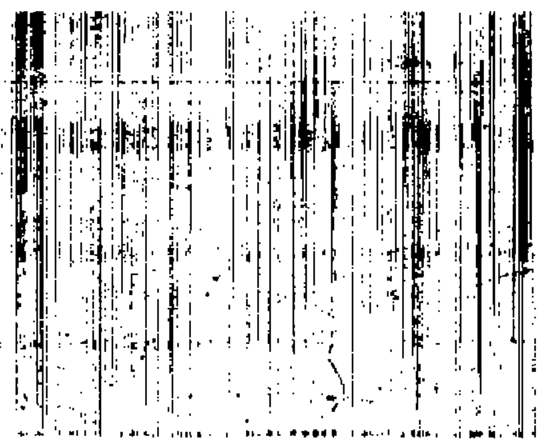
Figure 8. - Intercrystaline cracking and fracture surface in NiAl phase.



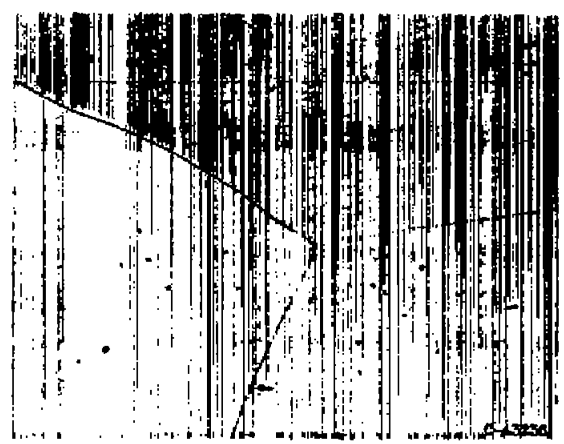
(a) 30-Percent-aluminum NiAl, homogenized at 2100° F for 48 hours.



(b) 30-Percent-aluminum NiAl, homogenized at 2400° F for 6 hours.

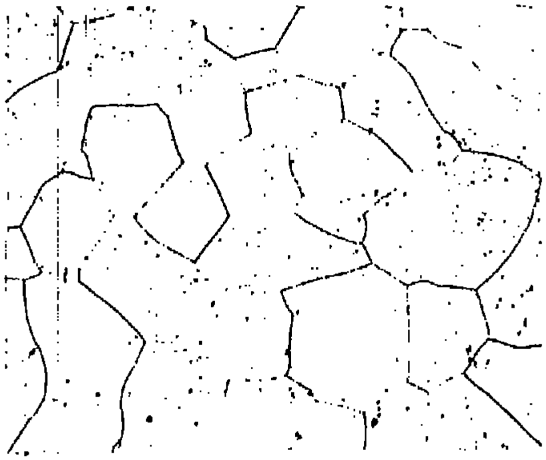


(c) 25-Percent-aluminum NiAl, homogenized at 2100° F for 48 hours.

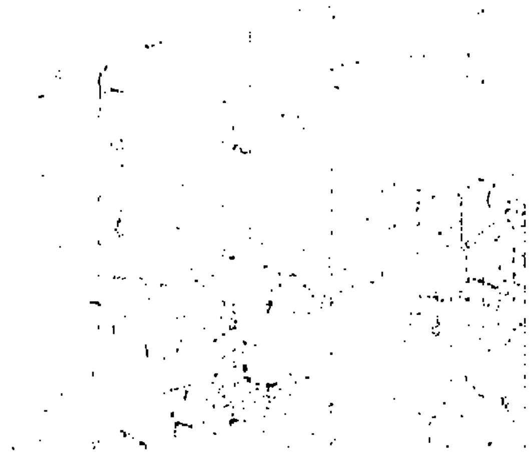


(d) 25-Percent-aluminum NiAl, homogenized at 2400° F for 6 hours.

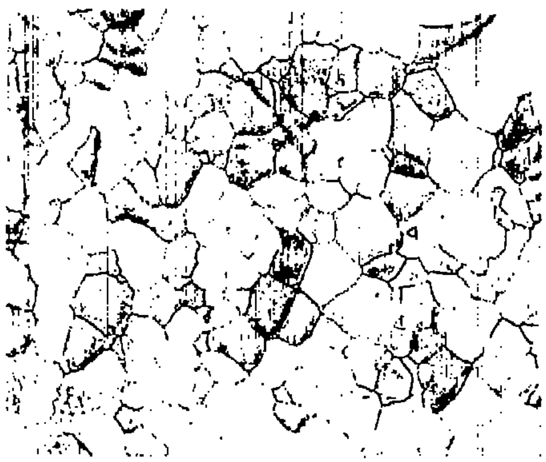
Figure 9. - Effect of homogenization temperature on microstructure of 25- and 30-percent-aluminum NiAl compositions. Vilella's reagent; X100.



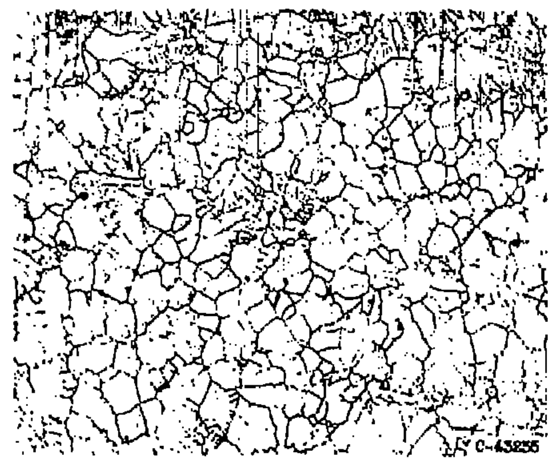
(a) 31.5-Percent-aluminum Al NiAl, homogenized at 2200° F for 48 hours.



(b) 31.5-Percent-aluminum plus 0.5-percent-molybdenum NiAl, homogenized at 2300°FF for 24 hours.

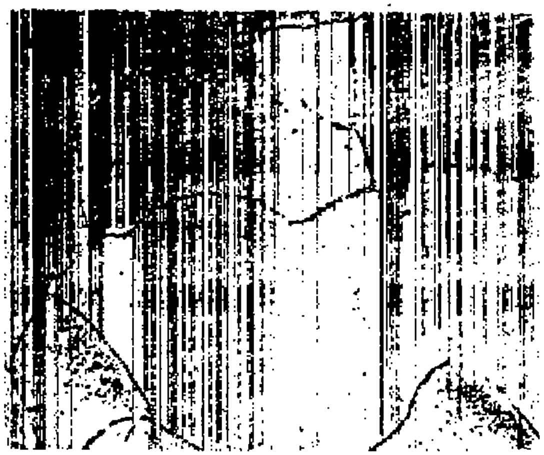


(c) 31.5-Percent-aluminum plus 1.0-percent-molybdenum NiAl, homogenized at 2300° F for 24 hours.

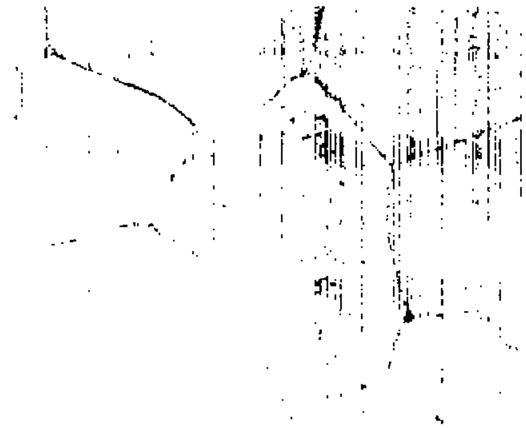


(d) 31.5-Percent-aluminum plus 2.0-percent-molybdenum NiAl, homogenized at 2300° F for 24 hours.

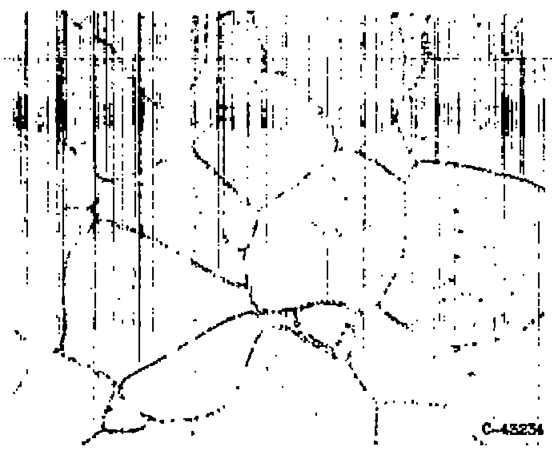
Figure 10. - Effect of molybdenum additions on grain size and microstructure of stoichiometric NiAl (31.5 percent aluminum). Etchant, 7 parts 5-percent sulphuric acid, 3 parts saturated solution of boric acid in water; X100.



(a) 31.5-Percent-aluminum plus 0.5-percent-molybdenum, homogenized at 2300° F for 24 hours.



(b) 31.5-Percent-aluminum plus 1.0-percent-molybdenum, homogenized at 2300° F for 24 hours.



(c) 31.5-Percent-aluminum plus 2.0-percent-molybdenum, homogenized at 2300° F for 24 hours.

Figure 11. - Effect of molybdenum additions on microstructure and grain size of stoichiometric NiAl (31.5 percent aluminum) composition. Etchant, 7 parts 5-percent sulphuric acid, 3 parts saturated solution of boric acid in water; X750.

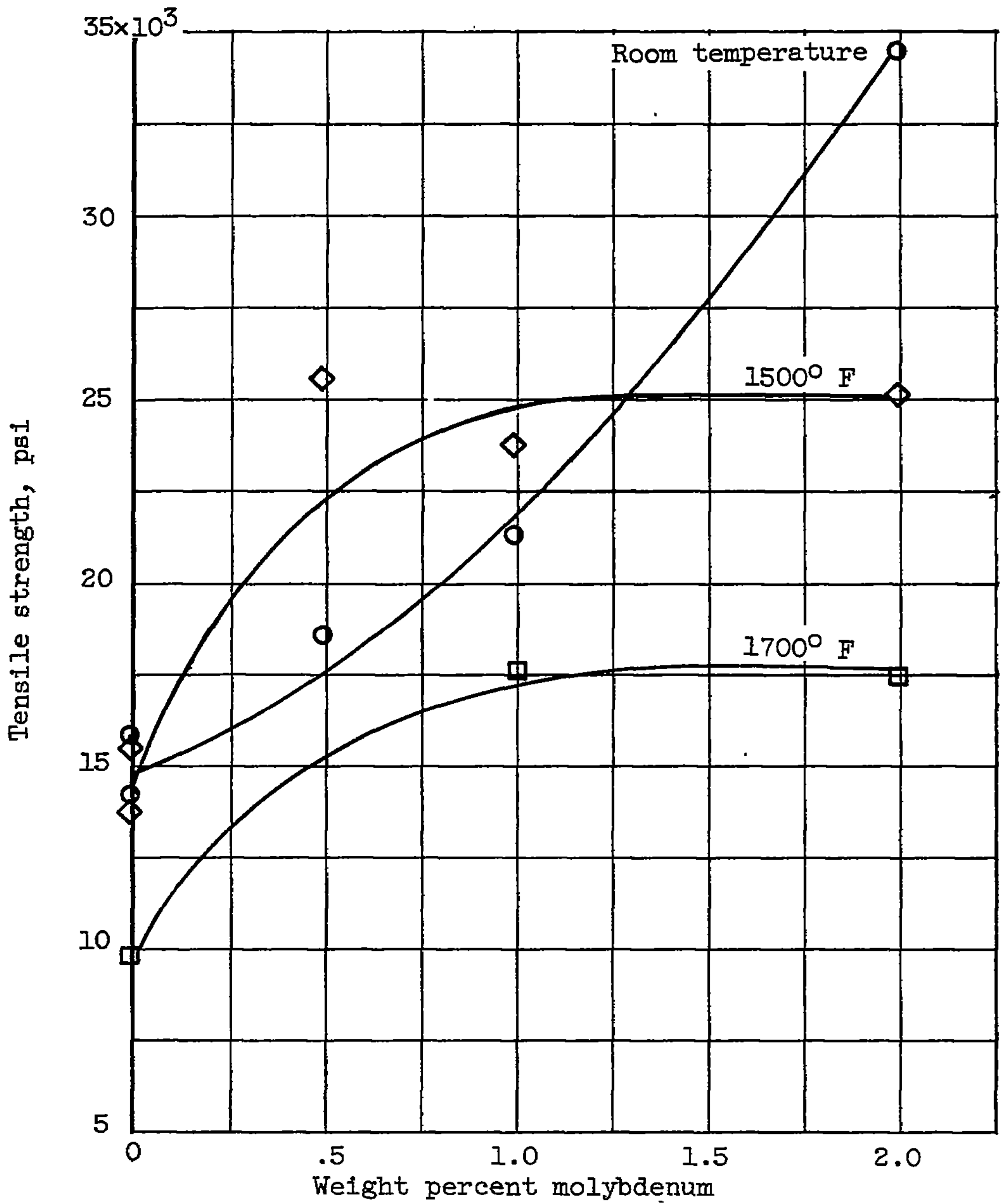


Figure 12. - Effect of molybdenum additions on strength of homogenized stoichiometric NiAl.